Jet-Tagged Back-Scattering Photons For Quark Gluon Plasma Tomography

Rainer J. Fries[a], Somnath De[b], Dinesh K. Srivastava[b]

[a]*Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77845, USA*
[b]*Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata - 700064, India*

Abstract

Direct photons are important probes for quark gluon plasma created in high energy nuclear collisions. Various sources of direct photons in nuclear collisions are known, each of them endowed with characteristic information about the production process. However, it has been challenging to separate direct photon sources through measurements of single inclusive photon spectra and photon azimuthal asymmetry. Here we explore a method to identify photons created from the back-scattering of high momentum quarks off quark gluon plasma. We show that the correlation of back-scattering photons with a trigger jet leads to a signal that should be measurable at RHIC and LHC.

Photons and dileptons have long been considered good probes of the hot and dense fireball created in high energy nuclear collisions. This is mostly due to the fact that the probability for particles without color charge to reinteract after their creation is negligible. Here we will mostly focus on photons though many of the arguments are equally valid for virtual photons and the dilepton pairs into which they decay.

Many sources of direct photons are known in high energy nuclear collisions: This includes (i) hard initial and fragmentation photons [1], which emerge from high momentum transfer scatterings of partons in the first instance of the collisions, either directly or as bremsstrahlung off quark and gluon jets. These photon sources are also active in collisions of protons. After the initial phase there is a pre-equilibrium phase that can last up to 1 fm/c in which (ii) pre-equilibrium photons can be emitted. The dynamics during the pre-equilibrium phase is not well understood and estimates of photon production under widely different assumptions are available [2, 3]. There is ample evidence that eventually an equilibrated quark gluon plasma (QGP) is created in collisions at energies available at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). This leads to the emission of (iii) thermal photon radiation [4, 5, 6, 7] which has been used as a thermometer for the hot nuclear matter created in those collisions [8]. As the fireball cools and expands confinement of partons into hadrons sets in. This could lead to (iv) photons from hadronization processes [9]. After hadronization the matter is still hot enough to emit (v) thermal photons from the hadronic phase [4]. Lastly we mention the source of photons that we will be interested in isolating here, (vi) photons from interactions of fast partons in QGP. It has been argued that interactions of fast quarks and gluons with QGP, that lead to energy loss of those partons can also produce photons through Compton scattering, annihilation and bremsstrahlung [10, 11, 12]. As in the purely electromagnetic sector Compton and annihilation photons in QCD can be emitted in back-scattering kinematics, making them a potentially high-yield source at large momenta. In these proceedings we discuss how these back-scattering

photons could be separated from other sources and what information is encoded in them [13].

Elastic photon-electron back-scattering is a well studied process in quantum electrodynamics with many technological applications. The phenomenon that the cross section for $\gamma + e \rightarrow \gamma + e$ exhibits a sharp peak in backward direction (i.e. the final photon going into the direction of the initial electron) can be used to create intense beams of high energy photons for experiments in material science, nuclear and particle physics [14, 15]. Typically $\sim$ eV photons from an intense laser beam are accelerated to $\sim$ GeV energies through back-scattering from an electron beam of large energy. In quantum chromodynamics the mixed process $g + q \rightarrow \gamma + q$ involves the same diagrams at leading order and exhibits the same Compton back-scattering peak. A similar peak can be observed for the annihilation process $q + \bar{q} \rightarrow \gamma + g$. In [10] some of us have estimated that a significant yield of high energy photons can be expected from quarks ($E_q \sim 1 - 100$ GeV) scattering off thermal gluons ($E_g \sim 200$ MeV) or thermal antiquarks in QGP. The rate of high energy Compton back-scattering and annihilation photons from high momentum quarks interacting with the medium is [10]

$$E_\gamma \frac{dN}{d^4 x d^3 p_\gamma} = \frac{\alpha \alpha_s}{4\pi^2} \sum_{f=1}^{N_f} \left(\frac{e_f}{e}\right)^2 \left[f_q(\mathbf{p}_\gamma, x) + f_{\bar{q}}(\mathbf{p}_\gamma, x)\right] T^2 \left[\ln \frac{3 E_\gamma}{\alpha_s \pi T} + C\right] \qquad (1)$$

where $C = -1.916$. α and α_s are the electromagnetic and strong coupling constant, T is the local temperature at x, f_q is the phase space distribution of fast quarks interacting with the medium and e_f is the electric charge of a quark with the index f running over all active quark flavors. This rate has subsequently also been calculated for virtual photons [16, 17].

We note that the photon rate is proportional to $T^2 \ln 1/T$, and hence the total yield of back-scattering photons is rather sensitive to the medium temperature. We can also see how the time evolution of the high momentum quark distribution f_q enters the yield linearly which leads to a power-law spectrum. Thus we might be able to go to large transverse momentum P_T to measure back-scattering photons. Because back-scattering happens throughout the time a parton propagates through QGP the rate is also sensitive to the energy loss of partons with time through f_q. It has been shown that back-scattering photons are an important contribution to the single inclusive direct photon spectrum at intermediate P_T of a few GeV/c [10, 11, 18]. However, the background of hard initial and fragmentation photons (dominant at larger P_T) and thermal photons (at lower P_T) is difficult to subtract. The search for photons from jet-medium interactions in single inclusive spectra has therefore been inconclusive. The same is true for the typical signature that jet-medium photons would leave on the azimuthal asymmetry v_2. It has been proposed that photons from jet-medium interactions have negative v_2 [19], unlike hard initial and thermal photons [20] which exhibit vanishing or positive v_2. Again the experimental situation so far is inconclusive [18].

Since back-scattering photons are produced by fast partons from a jet and jets prefer to be produced in back-to-back pairs we propose to use a jet trigger to look for an unambiguous signature. Specifically we suggest to trigger on a jet with an energy E_γ of a few 10 GeV and to look for direct photons in a narrow region in azimuthal angle ϕ on the away-side. Only hard initial photons and fragmentation photons have a similar correlation with a jet on the opposite side. These will be the sources that create the background for the measurement. All thermal and pre-equilibrium sources do not have a correlation with an away-side jet and can be neglected from the outset. Next we notice that fragmentation photons are concentrated at low z ($\lesssim 0.3$) where $z = E_\gamma / E_{\text{parent jet}}$ [1, 21]. Thus we can suppress the background from fragmentation (and induced bremsstrahlung) by choosing values of E_γ close to the trigger jet energy. We recall that

at leading order (LO) kinematics the transverse momenta of the trigger jet and the photon or parton on the other side are perfectly balanced. Energy loss before the conversion will shift the energy of back-scattering photons away from the trigger energy and thus to lower momentum compared to the background of hard initial photons. Beyond leading order the back-to-back correlation of both the back-scattering signal and the background (hard and fragmentation) photons are somewhat softened.

We are now going to present a numerical feasibility study. We use the JETPHOX code [22, 23] to calculate jet-photon and jet-hadron yields at LO and next-to-leading order (NLO) accuracies. Trigger jets were fixed around midrapidity in rather narrow windows in transverse energy. Then the photon spectrum in a sector of $\pm 15°$ around the away-side is considered. We use the PPM code [24, 25] to propagate leading jet partons of the away-side jet through a longitudinally boost-invariant fireball parameterization whose entropy dS/dy has been tuned to measured RHIC and LHC multiplicities. PPM calculates the energy loss of partons and the back-scattering process to create photons. The energy loss is tuned to describe measured single inclusive hadron spectra.
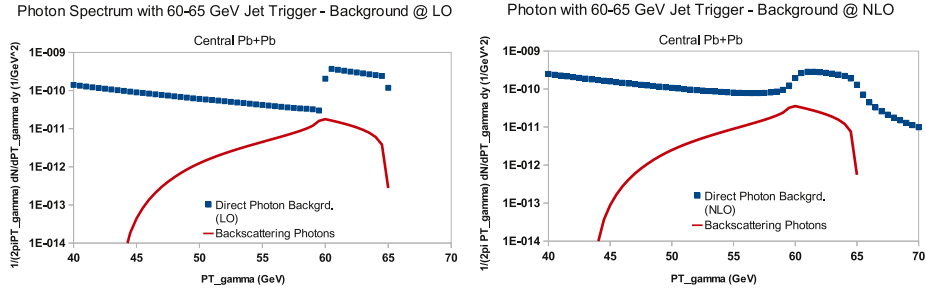

Figure 1: Left panel: photon spectra associated with trigger jets from 60-65 GeV in central Pb+Pb collisions at LHC at $\sqrt{s_{NN}} = 2.76$ TeV at LO accuracy. The yield of back-scattering photons (red solid line) is compared to the background of hard initial photons and fragmentation photons (blue squares). Right panel: same with background calculated at NLO accuracy and signal scaled with a K-factor of 2.

Fig. 1 shows typical results for LHC energies for a trigger jet window of $E_T = 60-65$ GeV/c, once in LO kinematics and for comparison also with the background calculated at NLO accuracy and the signal scaled with an appropriate K-factor of 2. We notice the strong correlation of the signal with the initial hard photon peak in the trigger window. However energy loss leads to a tail of the signal extending to lower momenta. In Fig. 2 we show the nuclear modification factor R_{AA} which we approximate by the ratio of signal (back-scattering) over the sum of signal and background (initial hard and fragmentation). Both the LHC case from Fig. 1 and a case for RHIC energies with a trigger jet energy $E_T = 30-35$ GeV/c are shown. R_{AA} is the most promising quantity to look for a back-scattering signature since we see a characteristic peak just below the trigger jet window. NLO kinematics washes out the signal but keeps it recognizable.

In summary, we have shown that the use of trigger jets facilitates the separation of back-scattering photons from other direct photons sources. For a trigger jet of a few 10 GeV energy direct photons on its away-side come mainly from initial hard processes and fragmentation of an away-side jet. However, back-scattering photons from the leading quark of an away-side jet lead to a characteristic enhancement of the nuclear modification factor for direct photons a few GeV
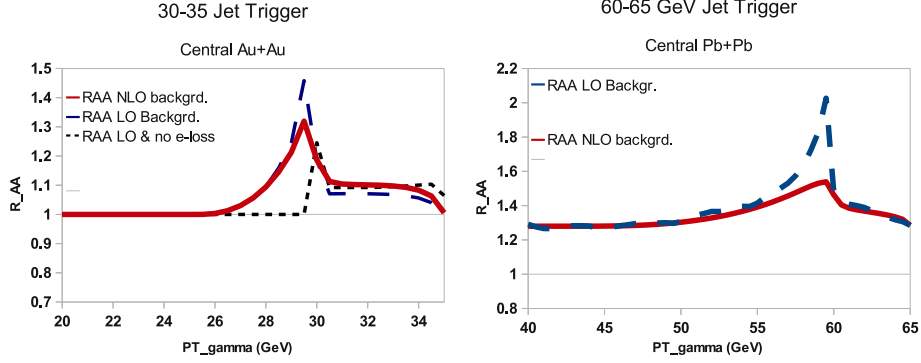
Figure 2: Left panel: The nuclear modification factor R_{AA} at LO accuracy for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with trigger jet energies between 30 and 35 GeV with (blue dashed line) and without (black dotted line) taking energy loss of leading partons into account. The NLO result with energy loss is also shown (red solid line). Right panel: LO and NLO results for the LHC case from Fig. 1.

below the trigger energy. The height of the back-scattering peak reflects the the temperature of the medium in which the back-scattering occurs while the shift in energy compared to the trigger jet energy is sensitive energy loss of the quark before back-scattering.

References

[1] J. F. Owens, Rev. Mod. Phys. **59**, 465 (1987)

[2] S. A. Bass, B. Muller and D. K. Srivastava, Phys. Rev. Lett. **90**, 082301 (2003)

[3] G. Basar, D. Kharzeev, D. Kharzeev and V. Skokov, preprint arXiv:1206.1334 [hep-ph]

[4] J. I. Kapusta, P. Lichard and D. Seibert, Phys. Rev. D **44**, 2774 (1991) [Erratum-ibid. D **47**, 4171 (1993)]

[5] R. Baier, H. Nakkagawa, A. Niegawa and K. Redlich, Z. Phys. C **53**, 433 (1992)

[6] P. Aurenche, F. Gelis, R. Kobes and H. Zaraket, Phys. Rev. D **58**, 085003 (1998)

[7] P. B. Arnold, G. D. Moore and L. G. Yaffe, JHEP **0112**, 009 (2001)

[8] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **104**, 132301 (2010)

[9] G. Chen, R. J. Fries, in preparation.

[10] R. J. Fries, B. Muller and D. K. Srivastava, Phys. Rev. Lett. **90**, 132301 (2003)

[11] R. J. Fries, B. Muller and D. K. Srivastava, Phys. Rev. C **72**, 041902 (2005)

[12] B. G. Zakharov, JETP Lett. **80**, 1 (2004)

[13] R. J. Fries, S. De and D. K. Srivastava, preprint arXiv:1208.6235 [nucl-th]

[14] R. H. Milburn, Phys. Rev. Lett. **10**, 75 (1963)

[15] F. R. Arutyunian and V. A. Tumanian, Phys. Lett. **4**, 176 (1963)

[16] D. K. Srivastava, C. Gale and R. J. Fries, Phys. Rev. C **67**, 034903 (2003)

[17] S. Turbide, C. Gale, D. K. Srivastava and R. J. Fries, Phys. Rev. C **74**, 014903 (2006)

[18] S. Turbide, C. Gale, E. Frodermann and U. Heinz, Phys. Rev. C **77**, 024909 (2008)

[19] S. Turbide, C. Gale and R. J. Fries, Phys. Rev. Lett. **96**, 032303 (2006)

[20] R. Chatterjee, E. S. Frodermann, U. W. Heinz and D. K. Srivastava, Phys. Rev. Lett. **96**, 202302 (2006)

[21] L. Bourhis, M. Fontannaz, J. P. Guillet and M. Werlen, Eur. Phys. J. C **19**, 89 (2001)

[22] S. Catani, M. Fontannaz, J. P. Guillet and E. Pilon, JHEP **0205**, 028 (2002)

[23] P. Aurenche, M. Fontannaz, J. -P. Guillet, E. Pilon and M. Werlen, Phys. Rev. D **73**, 094007 (2006)

[24] R. Rodriguez, R. J. Fries and E. Ramirez, Phys. Lett. B **693**, 108 (2010)

[25] R. J. Fries and R. Rodriguez, Nucl. Phys. A **855**, 424 (2011)